



Title	Benefits of Fast Cut Back Function of Thermal Generating Units in Constructing Self-healing Grids
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Benefits of Fast Cut Back Function of Thermal Generating Units in Constructing Self-healing Grids

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Abstract— This paper investigates the benefits of Fast Cut Back (FCB) function of thermal generating units in the self-healing control context. The FCB function enables a generating unit to reduce its output down to the auxiliary power level within seconds. The output can later be restored to normal level promptly without cold start process. This ability can provide dispatchers additional measures in both the emergency control and the restorative control. In this paper, the model of FCB function generating units is established. The benefits of the FCB function in system restoration context are described. Case studies are presented to show: 1) FCB function can be used to maintain generation balance in controlled separation; 2) FCB function reduces the restoration time in the blackstart stage.

Index Terms—Fast Cut Back, thermal generating units, generator shedding, post-separation control

I. INTRODUCTION

The general states and the category of control actions in power system operation has been well identified [1]. When the power grid moves from the secure normal state to the insecure normal state due to load increase, preventive control actions can be utilized to bring the grid back to secure normal state. When large disturbances happen, the grid transits to the emergency state, the grid could be brought back to normal state by corrective control, or could unfortunately transit into restoration state by some emergency control actions, such as controlled separation. In the latter scenario, the dispatches will perform restorative control actions to bring the grid back into the normal state.

The models and implementations of preventive control, corrective control, emergency control and restorative control have been studying independently due to lack of a generic methodology and lack of flexible power grid components. The aim of this paper is thus to present some preliminary results to connect emergency control with restorative control in the

context of system restoration by the advancement of thermal generating units control technology.

To achieve the self-healing feature, the grid should react to the disturbance promptly and facilitate all the available resources to re-establish secure state in corrective control, emergency control, and restorative control. The thermal generating units are generally regarded as less controllable, compared to the hydro units, due to the operating constraints of the thermal sub-system. Fortunately, the Fast Cut Back (FCB) function, equipped by some generating units in the power grid, provides the fast and flexible active power adjustment within a wide range (7%-100% of the nominal output). This feature opens the possibility to apply thermal generating units in both the emergency control and restorative control.

This paper investigates how the FCB function benefits the power grid under large disturbance to establish a fast and secure self-healing process. Specifically, the FCB function to bridge controlled separation to blackstart process will be studied.

On one hand, FCB function facilitates the power balance in controlled separation. The importance of controlled separation is well recognized. Using the slow coherency, paper [2] introduced a coherency-based method to search separation points. An ordered binary decision diagram (OBDD) method was employed in paper [3] to find potential splitting points. Papers [2] and [3] mainly considered steady-state constraints. Besides steady-state constraints, transient constraints, which were equivalent to an index, were introduced in paper [4]. One of important issues during controlled separation is to satisfy the power balance. For excessive generation areas with only traditional generating units, generator shedding may be needed to guarantee the power balance. However, FCB generating units can avoid generator shedding with the flexible active power adjustment in excessive generation areas after system separation.

On the other hand, generating units with FCB function can serve as blackstart resources to accelerate the blackstart

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process. If controlled separation cannot stop the loss of synchronism between different groups of generators, a cascading failure may result in a blackout. In this case, it is necessary to provide restoration strategies as quickly as possible. Though different systems have different characteristics and their strategies are also different, some common concerns in system restoration are shown in different system [5], such as optimal units start-up sequence[6], switching operation design, start-up of thermal units, overvoltage problems during unload transmission lines energization, frequency response of prime movers to a sudden load pick-up, cold load inrush, power factors[7] and coincident demand factors, protection issues, and so on. One of critical issues, which can influence the process of restoration, is to restart non-blackstart generating units. At this stage, some loads should be restored at the same time to avoid the overvoltage at the end of lines. However, load restoration slows down the progress of restarting generating units. For a FCB generating unit, it has a good capacity of leading phase operation, which can absorb enough reactive power at the stage of restarting non-blackstart units to control voltages. This function can speed up the restoration of non-blackstart generating units.

This paper is organized as follows. The steady-state mode of the FCB generating unit is established and compared with that of the normal thermal generating unit in Section II. Section III describes the model of post-separation controls and benefits of FCB generating units in post-separation controls. Section IV introduces the model of blackstart processes and benefits of FCB generating units. Two case studies are presented in Section V.

II. CHARACTERISTICS OF TRADITIONAL THERMAL UNITS AND FCB GENERATING UNITS

Fig. 1 shows the steady-state model of a traditional thermal generating unit.

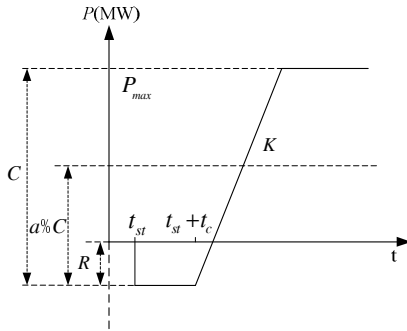


Figure 1. Traditional thermal generating unit model

P_{\max} is the maximum active power injected into the power system, C is the maximum active power that can be supplied by the generating unit. R is the requirement for restarting the generator, K is the ramping rate, t_{st} is the cranking time and $t_{st} + t_c$ is time of cranking to parallel. For a traditional thermal generating unit, it has a minimum output, i.e., $a\%C$. Below this minimum output, the generator can only increase its output rather than reduce the output.

Fig. 2 shows the steady-state model of a FCB generating unit.

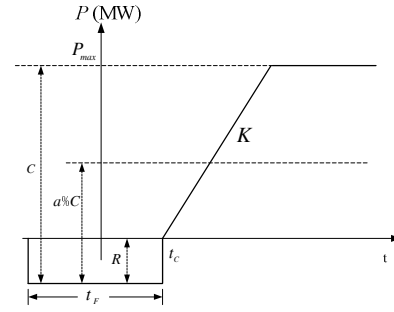


Figure 2. FCB generating unit model

P_{\max} is the maximum active power injected into power systems, C is the maximum active power that can be supplied by the FCB generating unit. $a\%C$ is the minimum output, K is the ramping rate, R is the electricity requirement of the plant. t_c is the time of cranking to parallel. t_F is the time of maintaining plant auxiliary power after a blackout.

The critical difference between the FCB generating unit and the traditional thermal generating unit is that the output of the FCB generating unit can be reduced to the auxiliary power instantaneously from a normal operating condition without the disconnection from the network after a blackout. For example, after a severe disturbance, the FCB generating unit can adjust its output to R rapidly and can maintain the output R for t_F . This function can avoid possible generator shedding in excessive generation areas, and make the generating units connect with the network instantaneously at the time t_c after clearing the disturbance.

Besides the fast cut back function, the FCB generating unit also has a larger capacity of leading phase operation, compared with the traditional thermal generating unit.

TABLE I shows the comparisons between the traditional thermal generating unit and the FCB generating unit.

TABLE I. COMPARISONS BETWEEN DIFFERENT GENERATING UNITS

Type	Operation just with auxiliary power	Connected with grid quickly	Large capacity of leading phase operation
Traditional thermal units	No	No	No
FCB units	Yes	Yes	Yes

III. THE MODEL OF POST-SEPARATION CONTROLS

Following a severe disturbance, different generators in different areas may be in the loss of synchronism. If normal controls cannot stop the loss, it is necessary to separate the interconnected system into several sub-systems to avoid a cascading failure. For example, Fig. 3 shows three potential sub-systems (PS for short), i.e., PS-1, PS-2 and PS-3.

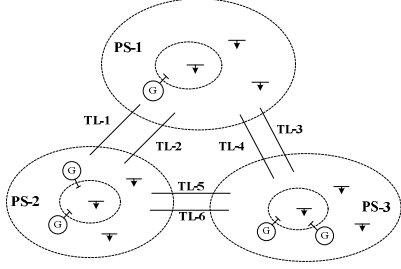


Figure 3. A system with three slow coherent groups

Assume that generators in PS-1 swing against generators in PS-2 and PS-3 following a severe disturbance. Separation relays installed on tie lines TL-1, TL-2, TL-3 and TL-4 separate the interconnected system into two islands, i.e., PS-1 and PS-2+PS-3. After system splitting, steady-state constraints should be satisfied to ensure the safety of each system.

$$PF(\mathbf{P}_{G(J)}, \mathbf{Q}_{G(J)}, \mathbf{P}_{D(J)}, \mathbf{Q}_{D(J)}) = 0 \quad (1)$$

$$\mathbf{A} \cdot \mathbf{P}_{G(J)} \leq \mathbf{P}_{G(J)} \leq \mathbf{A} \cdot \bar{\mathbf{P}}_{G(J)} \quad (2)$$

$$\mathbf{A} \cdot \mathbf{Q}_{G(J)} \leq \mathbf{Q}_{G(J)} \leq \mathbf{A} \cdot \bar{\mathbf{Q}}_{G(J)} \quad (3)$$

$$\underline{\mathbf{V}}_{B(J)} \leq \mathbf{V}_{B(J)} \leq \bar{\mathbf{V}}_{B(J)} \quad (4)$$

$$\underline{\mathbf{P}}_{L(J)} \leq \mathbf{P}_{L(J)} \leq \bar{\mathbf{P}}_{L(J)} \quad (5)$$

$$\mathbf{A} = \text{diag}[\underset{\substack{\uparrow \\ \text{Traditional} \\ \text{Thermal} \\ \text{Unit}}}{\mathbf{L}}, \underset{\substack{\uparrow \\ \text{FCB} \\ \text{Unit}}}{\mathbf{L}}, \alpha, \mathbf{L}] , \quad \alpha \in \{0,1\} \quad (6)$$

where $\mathbf{P}_{G(J)}$, $\mathbf{Q}_{G(J)}$, $\mathbf{P}_{D(J)}$ and $\mathbf{Q}_{D(J)}$ are vectors of real power of generating units, reactive power of generating units, real power of loads and reactive power of loads in the J th sub-system. $PF(\cdot)$ is the power flow equations. $\underline{\mathbf{P}}_{G(J)}$, $\bar{\mathbf{P}}_{G(J)}$ are the corresponding lower and upper limits of active power. $\underline{\mathbf{Q}}_{G(J)}$, $\bar{\mathbf{Q}}_{G(J)}$ are the corresponding lower and upper limits of reactive power. $\mathbf{V}_{B(J)}$ is the voltage vector of each bus, and $\underline{\mathbf{V}}_{B(J)}$, $\bar{\mathbf{V}}_{B(J)}$ are the corresponding lower and upper limits. $\mathbf{P}_{L(J)}$ is the real power on the line L , and $\underline{\mathbf{P}}_{L(J)}$, $\bar{\mathbf{P}}_{L(J)}$ are the corresponding lower and upper limits. The matrix \mathbf{A} denotes that generating units may not inject power into the network.

If the inequality (7) is satisfied, the outputs of some generating units should be zeros.

$$\sum_{i \in \Omega_{D(J)}} P_{D,i} < \sum_{i \in \Omega_{G(J)}} \underline{P}_{G,i} \quad (7)$$

where $\Omega_{G(J)}$ is the generator set of the J th sub-system, $\Omega_{D(J)}$ is the load set of the J th sub-system, $P_{G,i}^{(Min)}$ is the minimum output of the generator i in the J th sub-system, $P_{D,i}$ is the demand of the load i in the J th sub-system.

When there are only traditional thermal generating units in an excessive generation area, some generators may be rejected to guarantee the power balance. If some generating units have the FCB function, fast and flexible active power adjustments of them can avoid generator shedding.

However, controlled separation cannot guarantee the complete stability after splitting system. For scenarios that controlled separation cannot terminate out-of-step of the system, the system might go through a blackout. In this case, a restoration strategy should be determined as quickly as possible.

IV. THE MODEL OF BLACKSTART PROCESSES

At the stage of system restoration, one critical issue is to restart non-blackstart generating units rapidly. The objective is to restart them as quickly as possible. The model can be represented as follows.

$$T_K(x_K, \Theta_K) = \min_{x_K \in \Theta_K} (T_{K+1}(x_{K+1}, \Theta_{K+1}) + \Delta t_{x_K - x_{K+1}}) \quad (8)$$

$$\text{s.t. } PF(\Omega_{E(K)}, \mathbf{P}_{G(K)}, \mathbf{Q}_{G(K)}, \mathbf{P}_{D(K)}, \mathbf{Q}_{D(K)}) = 0 \quad (9)$$

$$\underline{\mathbf{V}}_B \leq \mathbf{V}_B \leq \bar{\mathbf{V}}_B \quad (10)$$

$$\underline{\mathbf{P}}_L \leq \mathbf{P}_L \leq \bar{\mathbf{P}}_L \quad (11)$$

$$\mathbf{P}_{G(K)}, \mathbf{Q}_{G(K)}, \mathbf{P}_{D(K)}, \mathbf{Q}_{D(K)} \in \mathbf{FS}(K) \quad (12)$$

where x_K denotes the generating units that are restored at the stage K , Θ_K is the set of all generating units and loads at the stage K , $\Delta t_{x_K - x_{K+1}}$ represents the time to restore generating units or loads x_{K+1} . $\Omega_{E(K)}$ includes all energized buses and lines at the stage K , $\mathbf{P}_{G(K)}$, $\mathbf{Q}_{G(K)}$, $\mathbf{P}_{D(K)}$ and $\mathbf{Q}_{D(K)}$ are vectors of real power of generating units, reactive power of generating units, real power of loads and reactive power of loads at the stage K , respectively. \mathbf{V}_B is the voltage at bus B , and $\underline{\mathbf{V}}_B$, $\bar{\mathbf{V}}_B$ are the corresponding lower and upper limits. \mathbf{P}_L is the real power of the line L , and $\underline{\mathbf{P}}_L$, $\bar{\mathbf{P}}_L$ are the corresponding lower and upper limits, $\mathbf{FS}(K)$ denotes feasible strategies of restoring generating units and loads at the stage K . The proposed method in paper [8] is employed to solve this model.

For a system with only traditional thermal generating units, it may need to restore some loads to avoid overvoltage when energizing lines. Actually, this will slow down the blackstart process. However, FCB generating units, with good capacities of leading phase operation, can absorb enough reactive power to control voltages at the end of lines, and this can reduce the capacity of restored loads to speed up the blackstart process.

V. CASE STUDIES

A. Benefits of FCB generating units in post-separation controls

- Simulations without FCB Generating Units

A two-area system is shown as Fig. 4. Assume that there is a disturbance and generators in the area 1 swing against generators in the area 2. The separation relays installed on the line 4-7 and the line 5-6 separate the system into two islands.

After separation, the active power provided by generating units in the first area is about 220 MW and the active power consumed by loads in the first area is about 101.3 MW. To ensure the power balance, it is necessary to reduce generation in the first area. Table II shows parameters of generating units. The sum of minimum outputs of generating units is 147 MW, which is larger than the power needed by customers. Therefore, some generators should be rejected to guarantee the power balance. In this case, the generating unit G2 can be rejected to guarantee the power balance after splitting the system, shown as Fig.5. Though generator shedding can ensure the power balance, it is a time-consuming task to restart the rejected generator after the clearing disturbance.

TABLE II. PARAMETERS OF GENERATING UNITS

Generator	Capacity (MW)	Minimum Output ratio	Minimum Output (MW)
1	120	35%	42
2	150	35%	52.5
3	150	35%	52.5
4	200	35%	70
5	200	35%	70

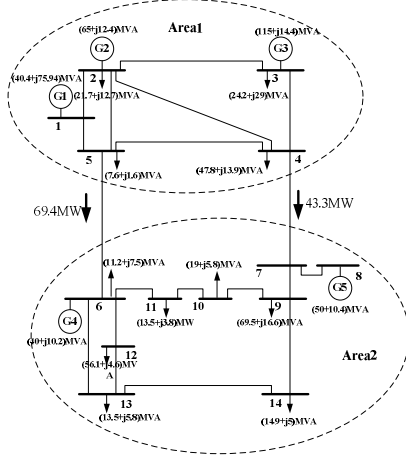


Figure 4. A two-area power system

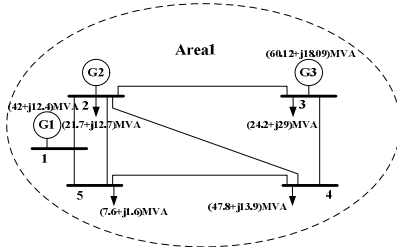


Figure 5. Area 1 after separation

- Simulations with FCB Generating Units

If G2 is a FCB generating unit, it can be in the FCB state after the system separation. In this process, it is not necessary to reject any generating units to balance the power. After splitting the system, the FCB generating unit G2 can just maintain the plant auxiliary power, and voltages and line power flows are the same with the scenario without the FCB generating unit. However, after clearing the disturbance, the generating unit G2 can be paralleled with the grid and increase the output with the fast ramping ratio instantaneously. This can avoid a long time to restart the non-blackstart generating units.

B. Benefits of FCB generating units in blackstart processes

The topology of the system is shown as Fig. 6. Five generating units are included in the system. G2, G3 and G5 are normal thermal generating units, and G1 is a blackstart unit. Two scenarios are studied. The first scenario is that G4 is a normal blackstart generating unit, and the second scenario is that G4 is a FCB generating unit. TABLE III shows parameters of generating units. The software MATPOWER is employed to calculate the power flow.

TABLE III. PARAMETERS OF GENERATING UNITS

Parameters	Generating Units				
	G1	G2	G3	G4	G5
Capacity (MW)	150	150	150	150	150
Startup power requirement (MW)	0	18	18	0	20
Ramping rate (MW/5min)	2	3	3	2	3
Minimum output ratio	20%	30%	30%	20%	30%
Crank to parallel (min)	0	70	60	0	60

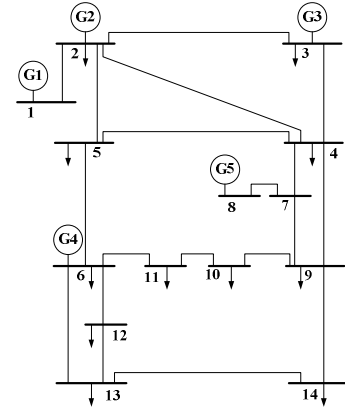


Figure 6. System topology

- Case 1: G1 and G4 are both normal BS generating units

Step 1) Through lines 1-2, 2-5 and 5-6, the generating unit G2 can be cranked by G4 and G1. It is need $t = (18\text{MW}/4\text{MW}) \times 5\text{min} = 22.5\text{min}$ to satisfy the startup requirement. At this time, the active power of G1 and G4 are both approximate 9 MW. To ensure that all voltages are in accepted ranges, it is necessary to pick up some loads, e.g., 10 MW at bus 5 (reactive power is 30% of active power). The time of providing extra power to loads is

$$t = (10\text{MW} / 4\text{MW}) \times 5\text{min} = 12.5\text{min}$$

Therefore, the time of restarting G2 is 35min.

Step 2): After restarting G2, G3 is cranked by G1 and G4 through the line 2-3. Some loads (e.g. 16MW at bus 5) should be picked up to limit the voltage.

The time of the whole process is

$$t = \frac{16\text{MW}}{4\text{MW} / 5 \text{ min}} + \frac{18\text{MW}}{4\text{MW} / 5 \text{ min}} = 42.5 \text{ min}$$

Step 3): Through lines 4-5, 4-7 and 7-8, G5 is cranked by G1 and G4, and some loads, e.g., 6 MW at bus 4, should be picked up.

The time of providing extra power to loads is

$$t = \frac{6\text{MW}}{4\text{MW} / 5 \text{ min}} = 7.5 \text{ min}$$

After $(70 - 42.5 - 7.5) = 20 \text{ min}$, the generating unit G2 can provide the power, the time of restarting G5 is

$$t = 20 \text{ min} + \frac{20\text{MW} - (4\text{MW} / 5 \text{ min}) \times 20 \text{ min}}{(2 + 2 + 3)\text{MW} / 5 \text{ min}} \approx 23 \text{ min}$$

Therefore, the whole time of restarting all NBS units, shown as Fig. 7, is

$$22.5 + 12.5 + 20 + 22.5 + 7.5 + 23 \approx 108 \text{ min}$$

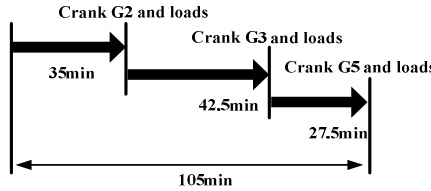


Figure 7. Restoration time of the first scenario

- Case 2: G1 is a BS unit and G4 is a FCB unit

Because of a large capacity of leading phase operation, FCB can absorb enough reactive power to control the voltage to accelerate the restoration.

Step 1): G2 is cranked by G1 and G4 through lines 1-2, 2-5 and 5-6. To control the voltage, G4 absorbs 20 Mvar reactive power. The time is

$$t = \frac{18\text{MW}}{4\text{MW} / 5 \text{ min}} = 22.5 \text{ min}$$

Step 2): G3 is cranked by G1 and G4 through the line 2-3. The absorbed reactive power of G4 does not change. The time of cranking G3 is

$$t = \frac{18\text{MW}}{4\text{MW} / 5 \text{ min}} = 22.5 \text{ min}$$

Step3): G1 and G4 prepare to crank G5. To control the voltages, the absorbed reactive power is adjusted to 35 Mvar. The consumed time is

$$t = \frac{20\text{MW}}{4\text{MW} / 5 \text{ min}} = 25 \text{ min}$$

Therefore, the whole time of restarting all NBS units (shown in Fig. 8) is about $22.5 + 22.5 + 25 = 70 \text{ min}$.

According to the results, the restoration of the scenario with a FCB unit is faster than that without a FCB unit.

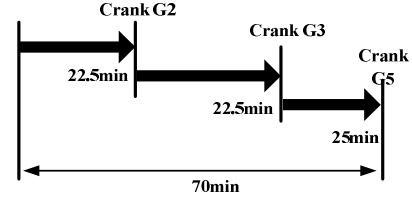


Figure 8. Restoration time of the second scenario

VI. CONCLUSIONS

This paper investigates the benefits of Fast Cut Back (FCB) function of thermal generating units in the self-healing control context. The FCB units can be utilized as a control measure to bridge post-separation controls to the blackstart process. Firstly, the characteristics of traditional thermal generating units and FCB generating units are established. Secondly, based on the special characteristics of FCB generating units, benefits of FCB generating units on post-separation controls and the blackstart process are analysed. Two test systems are presented to demonstrate the advantages of FCB generating units on post-separation controls and the blackstart process.

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